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(54) **CIRCUITS FOR AND METHODS OF IMPLEMENTING A GAIN STAGE IN AN INTEGRATED CIRCUIT**

(71) Applicant: **Xilinx, Inc.**, San Jose, CA (US)

(72) Inventor: **Vassili Kireev**, San Jose, CA (US)

(73) Assignee: **XILINX, INC.**, San Jose, CA (US)

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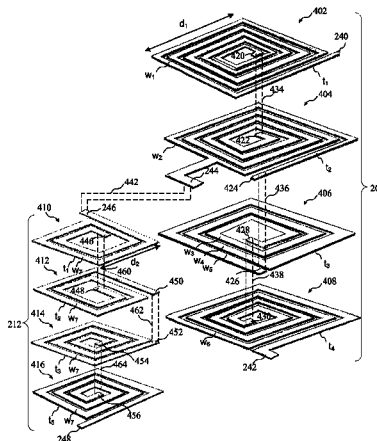
Assistant Examiner — Edward Chin

(74) *Attorney, Agent, or Firm* — John J. King; Lois D. Cartier

(57) **ABSTRACT**

A circuit for implementing a gain stage in an integrated circuit is described. The circuit comprises a first inductor formed in a first plurality of metal layers; a second inductor formed in a second plurality of metal layers, the second inductor coupled to a center tap of the first inductor; and wherein the second inductor has a diameter that is less than a diameter of the first inductor. A method of implementing a gain stage in an integrated circuit is also described.

20 Claims, 7 Drawing Sheets



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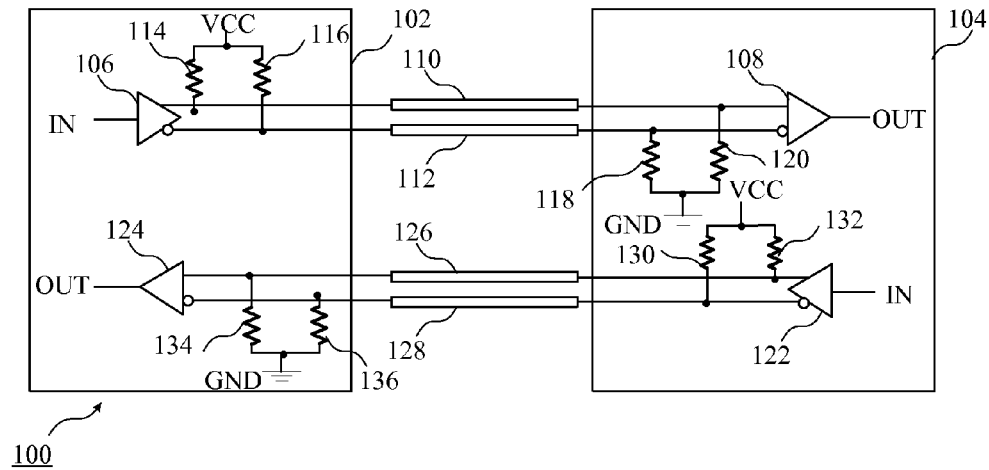


FIG. 1

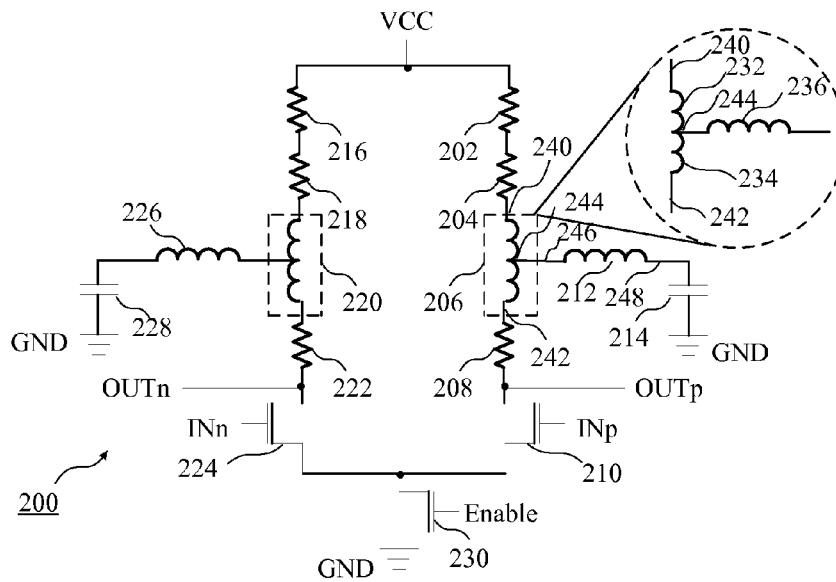


FIG. 2

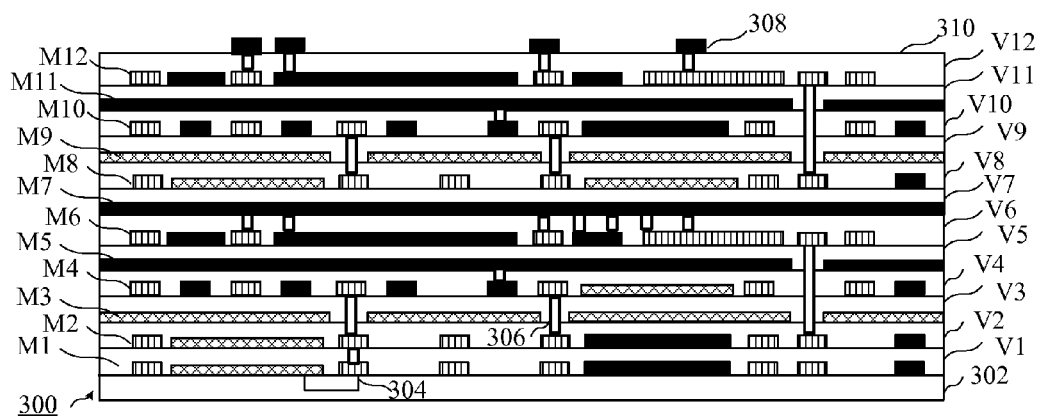


FIG. 3

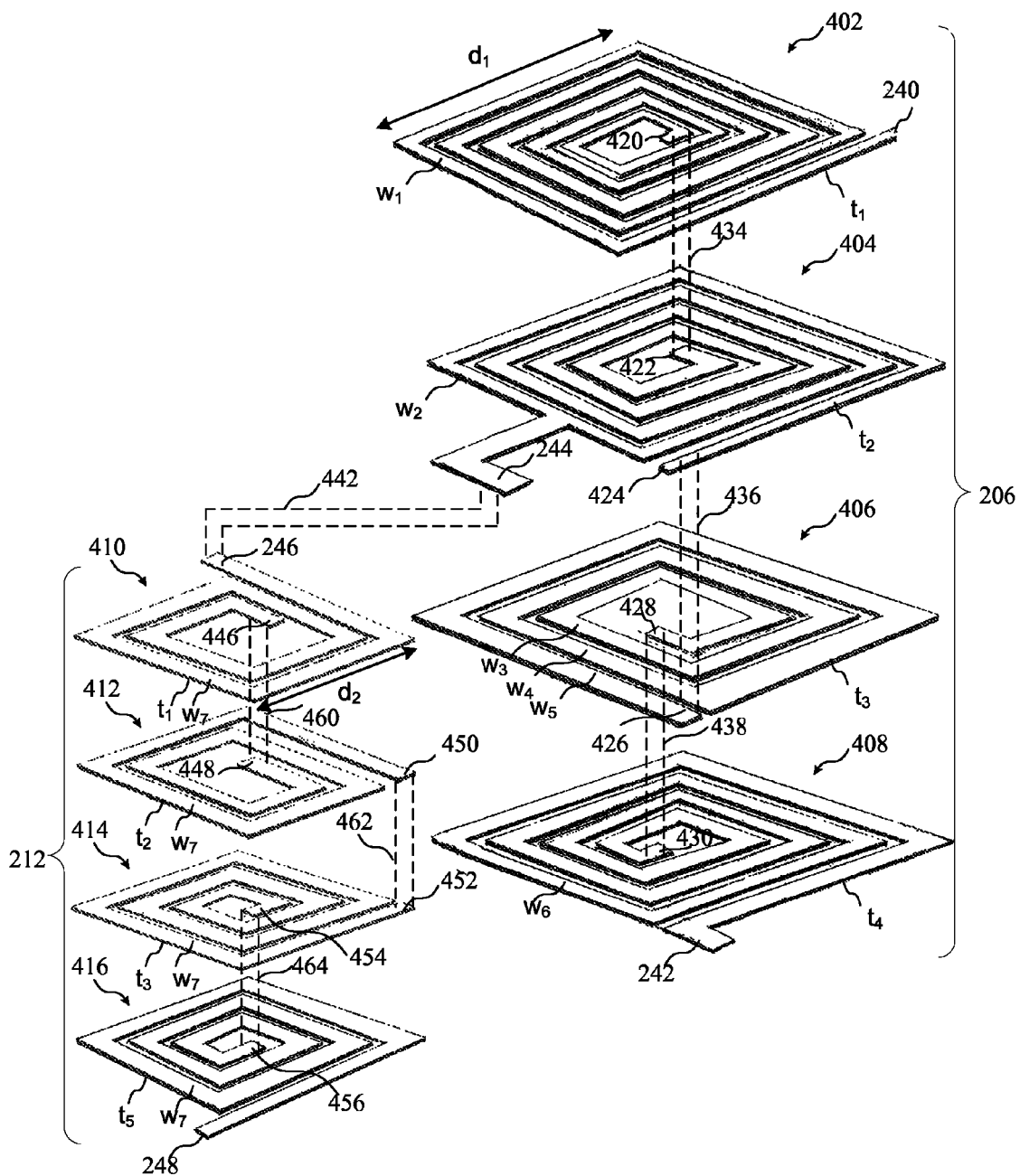


FIG. 4

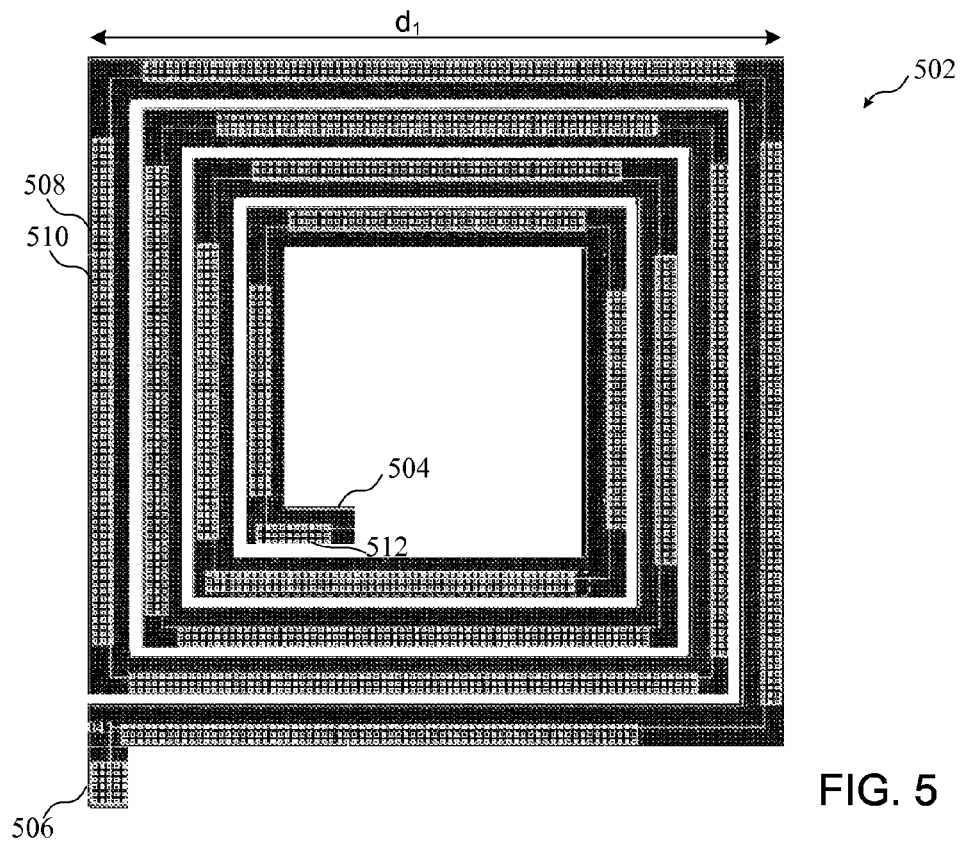


FIG. 5

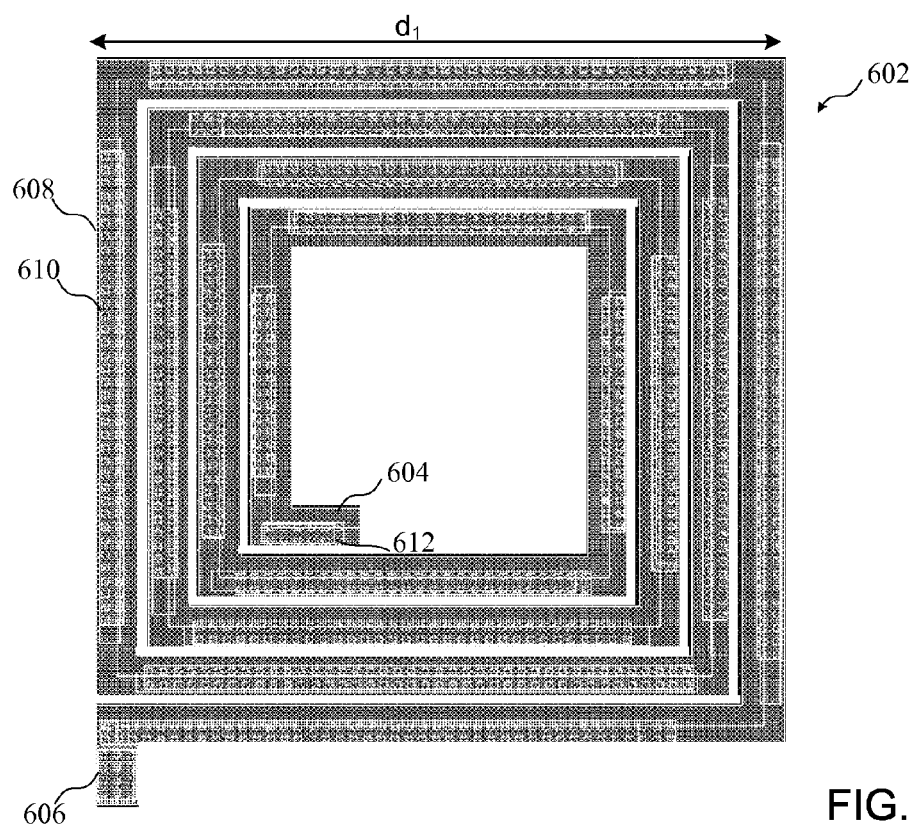


FIG. 6

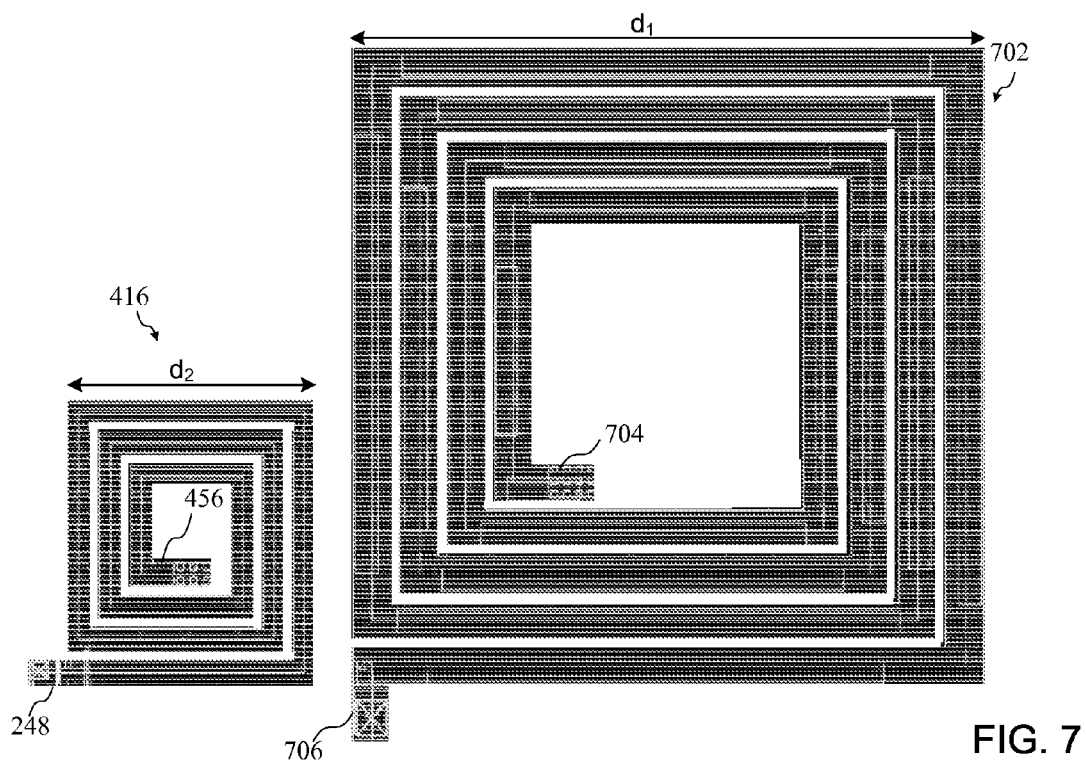


FIG. 7

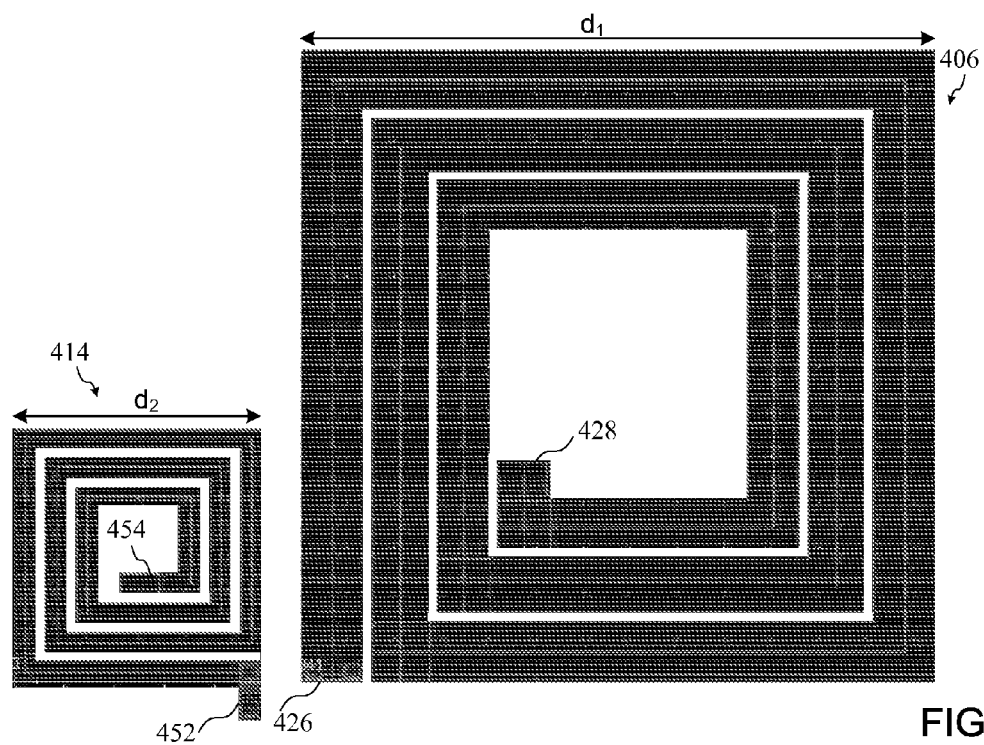
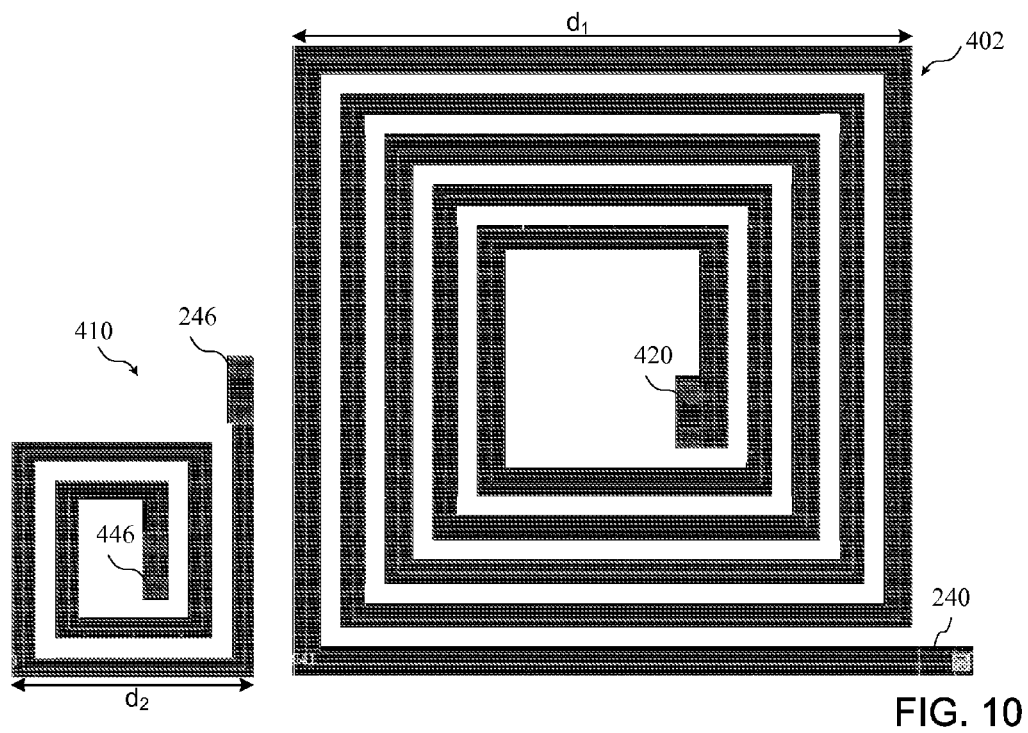
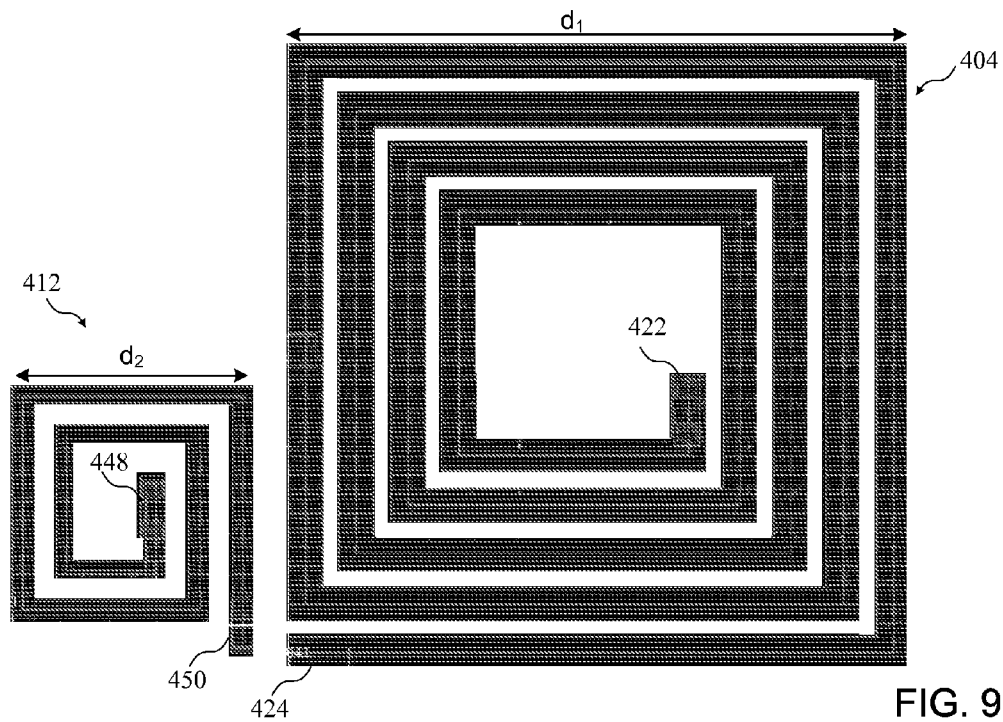


FIG. 8



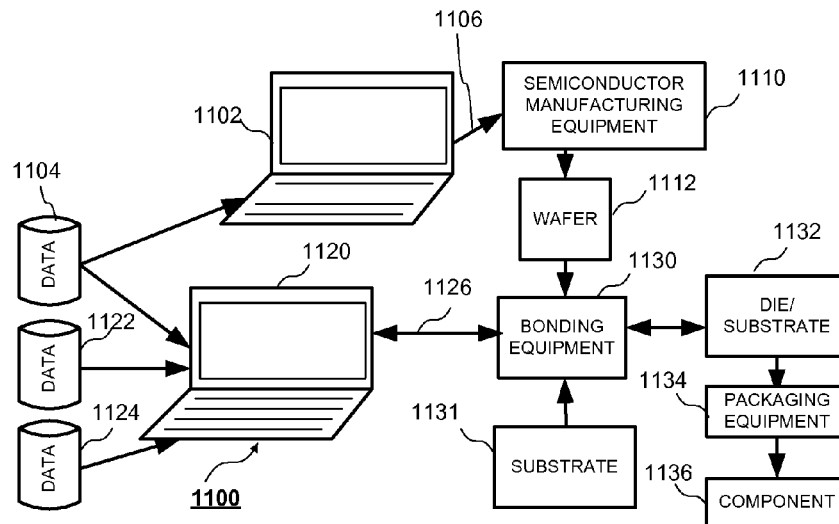


FIG. 11

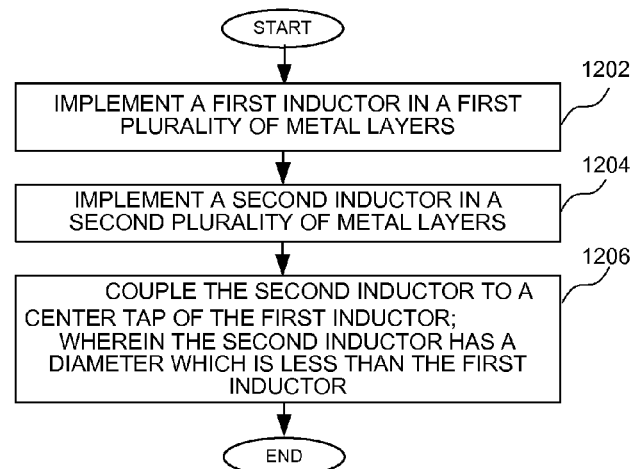


FIG. 12

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CIRCUITS FOR AND METHODS OF IMPLEMENTING A GAIN STAGE IN AN INTEGRATED CIRCUIT

TECHNICAL FIELD

The present invention relates generally to integrated circuits, and in particular, to circuits for and methods of implementing a gain stage in an integrated circuit.

BACKGROUND

The transfer of data is an important aspect of any integrated circuit device. While data may be transferred between integrated circuit devices through a lossy channel, one important aspect of any integrated circuit device is the efficient processing of the received data within an integrated circuit. As the performance requirements for integrated circuits continue to become more demanding, it is important to provide improved circuits and methods of transferring data. More particularly, there is always pressure to increase the speed of an integrated circuit while reducing both the size of the integrated circuit and power consumed by the integrated circuit. The same pressure is applied to the data links between integrated circuits. As the number of logic elements and memory cells in integrated circuits is increased, the density of data links and their power is also increased.

A received serial data stream experiences post-processing in an analog domain before it converted into the digital domain and de-serialized. This post-processing is implemented on multiple cascaded high-speed analog circuits amplifying and equalizing a signal, distorted and attenuated in a lossy channel, to the level necessary for error free sampling into the digital domain. Another usage of high-speed analog circuits is precise clocking needed for accurate sampling of the received data stream. All high speed analog circuits require high bandwidth and low power consumption that make it very attractive to use a peaking network based on a passive inductor. However, broad usage of a passive inductor for increasing bandwidth and reducing power consumption of high speed analog circuits is prevented by large inductor footprints that not only consume integrated circuit "real estate," but can also block power and signal distribution. A particular implementation of the inductor may also affect the resistance of the inductor and the magnetic coupling of the inductor, for example. Accordingly, it is difficult to implement an inductor of a high speed analog circuit which achieves many of the objectives of the circuit.

SUMMARY

A circuit for implementing a gain stage in an integrated circuit is described. The circuit comprises a first inductor formed in a first plurality of metal layers; a second inductor formed in a second plurality of metal layers, the second inductor coupled to a center tap of the first inductor; and wherein the second inductor has a diameter that is less than a diameter of the first inductor.

According to an alternate arrangement, a circuit for implementing a gain stage in an integrated circuit comprises a first transistor coupled to receive an input signal at a control terminal; and a T-coil inductor coupled to the first transistor, the T-coil inductor comprising a first inductor and a second inductor coupled to a center tap of the first inductor; wherein the second inductor has a diameter that is less than a diameter of the first inductor.

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A method of implementing a gain stage in an integrated circuit is also described. The method comprises implementing a first inductor in a first plurality of metal layers; implementing a second inductor in a second plurality of metal layers, coupling the second inductor to a center tap of the first inductor; wherein the second inductor has a diameter that is less than a diameter of the first inductor.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a system for transmitting data; FIG. 2 is a block diagram of a gain stage circuit which could be implemented in the system of FIG. 1;

FIG. 3 is a cross-sectional view of an integrated circuit having a plurality of metal layers;

FIG. 4 is an expanded view of an inductor of the gain stage circuit of FIG. 2.

FIG. 5 is a top plan view of a first metal layer of the inductor of FIG. 4 implemented in an integrated circuit;

FIG. 6 is a top plan view of a second metal layer of the inductor of FIG. 4 implemented in an integrated circuit;

FIG. 7 is a top plan view of a third metal layer of the inductor of FIG. 4 implemented in an integrated circuit;

FIG. 8 is a top plan view of a fourth metal layer of the inductor of FIG. 4 implemented in an integrated circuit;

FIG. 9 is a top plan view of a fifth metal layer of the inductor of FIG. 4 implemented in an integrated circuit;

FIG. 10 is a top plan view of a sixth metal layer of the inductor of FIG. 4 implemented in an integrated circuit;

FIG. 11 is a system for producing an integrated circuit; and

FIG. 12 is a flow chart showing a method of implementing an inductor in an integrated circuit.

DETAILED DESCRIPTION

Turning first to FIG. 1, a block diagram of a system 100 for transmitting data comprising a first transceiver 102 and a second transceiver 104 is shown. The first transceiver 102 comprises a transmitter circuit 106 coupled to a receiver circuit 108 in the second transceiver by a pair of transmission lines 110 and 112. The outputs of the transmitter 106 comprise differential outputs which are coupled by pull-up resistors 114 and 116 to a first reference voltage, such as VCC. The differential outputs may be a pair of complementary data, for example. The receiver circuit 108 is coupled to receive the differential signal at two inputs which are coupled by pull-down resistors 118 and 120 to a second reference voltage, such as ground. While the outputs of the transmitter circuits and the receiver circuit of FIG. 1 are coupled to pull-up and pull-down resistors, respectively, it should be understood that the outputs of the transmitter circuits could instead be coupled to pull-down resistors and that the inputs of the receiver circuits could instead be coupled to pull-up resistors.

In order to provide the bi-directional transfer of data, a transmitter circuit 122 in the second transceiver is coupled to a receiver circuit 124 in the first transceiver by a pair of transmission lines 126 and 128. The outputs of the transmitter 122 also comprise differential outputs which are coupled by pull-up resistors 130 and 132 to the reference voltage VCC. The receiver circuit 124 is coupled to receive the differential signal at two inputs which are coupled by pull-down resistors 134 and 136 to ground. While the system 100 of FIG. 1 is an example of a portion of a system having transceivers, it should be understood that the receiver circuits described in more detail below could be implemented in any type of system having transceivers for transmitting and receiving data.

Turning now to FIG. 2, a block diagram of a gain stage circuit **200** which could be implemented as gain stage **108** or **124** of FIG. 1 for example is shown. In particular, the gain stage circuit **200** comprises a plurality of elements coupled in series for generating a first output (OUTp). The elements coupled in series include a first resistor **202**, a second resistor **204**, an inductor **206**, a resistor **208**, and a transistor **210** as shown. The transistor **210** is coupled to receive a first input data signal (INp) of a complementary pair of data signals at its gate, and generates the first output data signal OUTp at its drain.

A second series of elements is coupled to receive a second differential input data signal of the complementary pair of data signals and generate a second differential output data signal. In particular, the elements of a second group of elements coupled in series include a first resistor **216**, a second resistor **218**, an inductor **220**, a resistor **222**, and a transistor **224**. The transistor **224** is coupled to receive a second input data signal (INn) of the complementary pair of data signals at its gate and generate a second output data signal OUTn at its drain. A control transistor **230** may be coupled to receive an enable signal at its gate to enable the gain stage.

As shown in the expanded view of FIG. 2, the inductor **206** comprises T-coils with a first inductor **232** and a second inductor **234** coupled in series at a center tap **244**, with a third inductor **236** coupled to the center tap **244**. The second coil **212** extends between a first terminal **246** and a second terminal **248**, where the first terminal **246** is coupled to the center tap **238**. A capacitor **214** is coupled between second terminal **248** and ground (GND). It should be noted that the inductor **236** is not a physical element in the circuit, but is included to model the negative inductance in the circuit and compensate for the negative inductance (as a result of the mutual coupling of the first inductor **232** and the second inductor **234**) by providing positive inductance through inductor **212**. It should also be noted that, unlike resistor **202** which is an element implemented in the gain stage circuit **200**, the resistors **204** and **208** represent parasitic impedances of the inductor. The inductor **212** may have an inductance which is less than the inductance of inductor **206**. As will be described in more detail in FIGS. 4-10, the smaller inductance of inductor **212** can be achieved by having a smaller diameter of coils of the inductor **212** compared to the coils of inductor **206**. The implementation of the inductors **206** and **212** will be described in more detail in reference to FIGS. 4-10. Further, it should be noted that the inductor **220** is implemented in the same way as inductor **206** as set forth above. An inductor **226** is coupled to a center tap of inductor **220**, and a capacitor **228** is coupled between inductor **226** and ground (GND).

Turning now to FIG. 3, a cross-sectional view shows an integrated circuit **300** having a plurality of metal layers. As shown in FIG. 3, metal layers having conductive traces for different signal types are provided. By way of example, a ground trace is indicated in solid black, a signal trace is indicated by cross-hatched lines, and a power voltage trace is indicated by vertical lines. The integrated circuit includes a substrate **302** having circuit elements **304** which are coupled to various interconnect elements formed in a first metal layer M1 on the surface of the substrate **302**. Vias, shown for example by **306**, enable the connection of various traces to traces in other layers. The metal layers are separated by a dielectric layers, shown here as the white material not occupied by the metal traces or vias formed in the dielectric material of the dielectric layers. External contacts **308** may be implemented as input/output (I/O) contacts on a top surface **310** of the integrated circuit as shown for enabling the input

and output of data associated with the circuit elements **304** and providing reference voltages, such as power and ground to the circuit elements.

The integrated circuit of FIG. 3 as shown comprises 12 metal layers M1-M12, and 12 corresponding via layers V1-V12. As will be described in more detail below, the metal layers may have different thicknesses and be used for different types of signals or circuit elements, including the inductors of FIG. 2 as shown and described in more detail below in reference to FIGS. 4-10. While 12 metal layers and corresponding via layers are shown, it should be understood that greater or fewer layers could be implemented.

Turning now to FIG. 4, an expanded view shows an inductor of the gain stage circuit of FIG. 2. As shown in FIG. 4, the inductor **206** has 4 coils **402-408** implemented in at least 4 metal layers, where each coil has a plurality of loops. Similarly, the inductor **212** comprises four coils **410-416**, where each of the coils has a plurality of loops. The coil **402** extends from a first terminal **240** to a second terminal **420** and has 4 loops as shown. The coil **404** extends from the first terminal **422** to a second terminal **424**, and also has 4 loops. The coil **406** extends from a first terminal **426** to a second terminal **428** and has three loops. Finally, the coil **408** extends from a first terminal **430** to the second terminal **242** and has four loops.

The loops of the four coils are formed in different metal layers, and the coils are coupled together by vias between the metal layers. More particularly, the second terminal **420** of the coil **402** is coupled to the first terminal **422** of the coil **404** by a via **434**. The second terminal **424** of the coil **404** is coupled to the first terminal **426** of the coil **406** by a via **436**, and the second terminal **428** of the coil **406** is coupled to the first terminal **430** of coil **408** by a via **438**.

The inductor **212** is coupled to the center tap **244** of the inductor **206** by a via **442** at the terminal **246**. A second terminal **446** of the coil **402** is coupled to the first terminal **448** of the coil **412** by a via **460**. The second terminal **450** of the coil **412** is coupled to a first terminal **452** of the coil **414** by a via **462**, and a second terminal **454** of the coil **414** is coupled to the first terminal **456** of coil **416** by a via **464**.

The metal layers used to form each of the inductors **206** and **212** may be consecutive metal layers and may have terminals which are coupled by a via in a single via layer. As will be described in more detail below, a given coil may be formed using a plurality of metal layers. The plurality of metal layers used to form inductor **212** may be the same as or a subset of the plurality of metal layers used to form inductor **206**.

Top plan views of various metal layers are shown in FIGS. 5-10. According to one arrangement of metal layers, the bottom coil **408** may be formed from a series of coils in different layers which are connected by vias between the metal layers. As shown in FIG. 5, a coil **502** comprises 4 loops which extend from the terminal **504** to the terminal **506**. Conductive elements **508** comprising a plurality of vias **510**, shown on each side of each loop, enable connecting the coil **502** to a coil **602**. The vias **512** correspond to the vias **438** to couple terminal **430** of coil **408** to terminal **428** of coil **406**. The coil **408** as shown is a square structure having a diameter d_1 . However, it should be understood that other shapes, such as rectangular or circular loops, could be implemented.

The coil **602**, which also extends from a first terminal **604** to a second terminal **606**, has substantially the same size and shape as the coil **502**. Similarly, conductive elements **608** comprising a plurality of vias **610**, shown on each side of each loop, enable connecting the coil **602** to a coil **702**. The coil **702**, which also extends from a first terminal **704** to a second terminal **706**, has substantially the same size and shape as the coils **502** and **602**. The coils **502**, **602** and **702** together form

the bottom coil **408**, where the terminals **504**, **604**, and **704** are a part of the terminal **430** and the terminals **506**, **606**, and **706** are a part of the terminal **242**. That is, each of the plurality of vias **508**, **608** and **708** on each side of the loop for each loop in the metal layers of FIGS. **5**, **6**, and **7** form a single coil with 4 loops having a thickness of the three metal loops and the vias between the metal layers. Also shown in FIG. **7** is the coil **416**, which is only made up of a single metal layer. That is, unlike the coil **408** which is made up of traces in 3 metal layers coupled together by vias, coil **416** comprises metal traces only in the metal layer having coil **702**. The coil **416** is also a square coil having a diameter d_2 which is less than the diameter d_1 , where d_1 could be approximately 13 micrometers and d_2 could be approximately 5 micrometers.

The remaining coils **406**, **404**, and **402** of the inductor **206** are also formed in a single metal layer with a corresponding coil **414**, **412** and **410** of the inductor **212**. More particularly, the coil **406** comprises 3 loops, where the width of traces is generally decreasing from the outer loop to the inner loop. That is, w_3 is generally wider than w_4 , which is generally wider than w_5 . The resistance of the loop is minimized by having wider routing with gradual reduction from the edge to the center. As shown in FIG. **9**, each of the sides of the loops of coil **404** (which has 4 loops) has approximately the same width, which is generally less than the widths of the various traces of coil **406**. Finally, each of the sides of the loops of coil **402** (which has 5 loops) has approximately the same width w_1 , which is generally less than the widths of the various traces of coil **404**. The width w_2 of coil **404**, which has only 4 loops, is generally greater than w_1 of coil **402**, which has 5 loops. The thickness of the metal layers can vary, where the thickness of the lower metal layers starting from M1 is less than the thickness of the upper metal layer M12. While the coils of the inductors of FIG. **4** could be implemented in any the metal layers, the inductors are preferably implemented in the upper metal layers.

Inductors **402** and **410** may be formed in metal layer M12 and have a thickness t_1 , inductors **404** and **412** may be formed in metal layer M11 and have a thickness t_2 , inductors **406** and **414** may be formed in metal layer M10 and have a thickness t_3 , and inductors **408** and **416** may be formed in metal layer M9. As set forth above, inductor **408** may be formed in a plurality of metal layers to provide an increased thickness t_4 compared to a thickness of the metal layer M9 alone. However, the lower coil **416** of inductor **212** may be formed in the metal layer M9 alone and has a thickness t_5 . The widths of the traces of coils **410-416** have a value w_7 , which is approximately equal.

The T-coil implementation with the smaller coil **212** provides up to 3.5 times the bandwidth (BW) extension of internal circuitry (compared to conventional T-coils) based on a multi-layer inductor **206** having a diameter below 15 micrometers and a multi-layer inductor **212** having a diameter of 5 micrometers. The small T-coil **206** may have high self-resonance frequency, but may suffer from high magnetic coupling between coils when implemented alone. In order to overcome these drawbacks, an additional series inductor **212** coupled to the center tap of the inductor **206** compensates for excessive magnetic coupling. The additional inductor **212** also helps to reduce the effect of T-coil resistance on the operation point and DC gain of the stage. In addition, the arrangement set forth above may simplify the design of a bias circuit for the multiple sequential stage by having different loading, but using the same biasing method. That is, fine tuning of the gain stage can be performed by only changing the dimension of coil **212** to enable keeping DC bias same for all CML stages.

The circuits set forth above may be implemented in a current mode logic (CML) stage, for example. An internal CML stage has less power consumption compare to a conventional receiver input. Current in the driver is in the range of 2-5 mA compare to 10 mA for a conventional receiver. This allows for the same multi-layer structure to make the footprint 2x-3x smaller than an input T-coil, and therefore have a smaller parasitic capacitance or a larger self-resonance frequency. However, the cost for this performance improvement is additional series resistance from thinner metal lines, and a variation over temperature that is on the order of 0.3-0.4% per K that can reach approximately 100% over PVT.

Another problem related to the small footprint of T-coil **206** is an increase of magnetic coupling between T-coil branches associated with smaller size. The configuration results in magnetic coupling k of approximately 0.6-0.8, while a required magnetic coupling is easily achievable with a larger footprint having a magnetic coupling k of approximately 0.2-0.6. If mutual inductance is large, the effective coupling between coils can be controlled by adding inductance to the center tap. Accordingly, large mutual coupling between the coils is beneficial by allowing larger inductance of the branch, but the smaller interwindings provide smaller parasitic resistance and area.

Turning now to FIG. **11**, a system for producing an integrated circuit is shown. The system **1100** comprises computer aided design (CAD) equipment **1102**, which could be any computer adapted to run CAD software. The CAD equipment **1102** receives data, such as a master pinlist **1104**, and is coupled by a communication link **1106** to semiconductor manufacturing equipment **1110**. The semiconductor manufacturing equipment **1110** generates a wafer **1112** having a plurality of die, as is well known in the art.

CAD equipment **1120**, which is also coupled to receive the master pinlist **1104**, receives a bonding diagram **1122** and substrate artwork **1124**. The CAD equipment **1120** is coupled by a communication link **1126** to bonding equipment **1130**. The communication links **1106** and **1126** could be any wired or wireless communication link. The bonding equipment generally provides wire bonds from a die from the wafer **1112** to a substrate **1131** receiving the die, as will be described in more detail in reference to other figures. The die/substrate **1132** is coupled to packaging equipment **1134** which generates a finished component **1136**, such as an integrated circuit package. Although the system of FIG. **11** provides various elements required for producing an integrated circuit package, it should be understood the elements shown in FIG. **11** could be combined, or additional elements could be provided. In any configuration, the system of FIG. **11** enables generating the required traces in the metal layers to implement the circuit of FIG. **1**, and particularly the loops of the inductors shown in FIGS. **4-10**.

Turning now to FIG. **12**, a flow chart shows a method of implementing an inductor in an integrated circuit. A first inductor is implemented in a first plurality of metal layers at a step **1202**. A second inductor is implemented in a second plurality of metal layers at a step **1204**. The second inductor is coupled to a center tap of the first inductor at a step **1206**, wherein the second inductor has a diameter which is less than the first inductor. The methods of FIG. **12** could be implemented using the circuits of FIGS. **1-10** as described above, or other suitable circuits. While particular elements are shown in FIG. **12**, it should be understood that additional details related to the elements of FIG. **12**, or additional elements, can be found in the description of FIGS. **1-10**.

It can therefore be appreciated that the new and novel gain stage circuit and method of transmitting data have been

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described. It will be appreciated by those skilled in the art that numerous alternatives and equivalents will be seen to exist which incorporate the disclosed invention. As a result, the invention is not to be limited by the foregoing embodiments, but only by the following claims.

What is claimed is:

1. A circuit for implementing a gain stage in an integrated circuit, the circuit comprising:

a first inductor in a first plurality of metal layers, the first inductor having a plurality of coils including a first coil in a first metal layer and having a center tap, the first coil coupled by a first via to a second coil in a second metal layer above the first metal layer and coupled by a second via to a third coil in a third metal layer below the first metal layer;

a second inductor in a second plurality of metal layers, the second inductor coupled to the center tap of the first inductor; and

wherein the second inductor has a diameter that is less than a diameter of the first inductor.

2. The circuit of claim 1, wherein:

the integrated circuit comprises a plurality of metal layers extending from a lower metal layer to an upper metal layer; and

the first inductor is situated above the lower metal layer.

3. The circuit of claim 1, wherein:

the first inductor further comprising a fourth coil on a bottom layer of the first inductor; and

the first and second coils have traces of smaller widths than traces of the third and fourth coils.

4. The circuit of claim 3, wherein the third coil has a plurality of loops having traces of an outer loop with widths that are larger than widths of traces of an inner loop.

5. The circuit of claim 3, wherein the fourth coil comprises a plurality of metal layers.

6. The circuit of claim 1, wherein:

the gain stage comprises a current mode logic gain stage; and

the first inductor and the second inductor are coupled to transmit first data of a complementary pair of data.

7. The circuit of claim 6, further comprising:

a third inductor comprising the first plurality of metal layers; and

a fourth inductor comprising the second plurality of metal layers and coupled to a center tap of the third inductor; wherein the fourth inductor has a diameter that is less than a diameter of the third inductor; and

wherein the third inductor and the fourth inductor are coupled to transmit second data of the complementary pair of data.

8. A circuit for implementing a gain stage in an integrated circuit, the circuit comprising:

a first transistor coupled to receive an input signal at a control terminal; and

a T-coil inductor coupled to the first transistor, the T-coil inductor comprising a first inductor and a second inductor coupled to a center tap of the first inductor, the first inductor having a plurality of coils including a first coil in a first metal layer and having a center tap, the first coil coupled by a first via to a second coil in a second metal layer above the first metal layer and coupled by a second via to a third coil in a third metal layer below the first metal layer;

wherein the second inductor has a diameter that is less than a diameter of the first inductor.

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9. The circuit of claim 8, wherein coils of the second inductor are outside coils of the first inductor.

10. The circuit of claim 8, wherein:

the integrated circuit comprises a plurality of metal layers; and

the first inductor comprises a first plurality of metal layers and the second inductor comprises a second plurality of metal layers.

11. The circuit of claim 10, wherein:

the integrated circuit comprises a plurality of metal layers extending from a lower metal layer to an upper metal layer; and

the first inductor is situated above the lower metal layer.

12. The circuit of claim 10, wherein:

the first inductor further comprising a fourth coil on a bottom layer of the first inductor; and

the first and second coils have traces of smaller widths than traces of the third and fourth coils.

13. The circuit of claim 12, wherein the second coil has a plurality of loops having traces of an outer loop with widths that are larger than the widths of traces on an inner loop.

14. The circuit of claim 8, wherein:

the gain stage comprises a current mode logic gain stage; and

the first inductor and the second inductor are coupled to transmit first data of a complementary pair of data.

15. A method of implementing a gain stage in an integrated circuit, the method comprising:

implementing a first inductor in a first plurality of metal layers, the first inductor having a plurality of coils including a first coil in a first metal layer and having a center tap, the first coil coupled by a first via to a second coil in a second metal layer above the first metal layer and coupled by a second via to a third coil in a third metal layer below the first metal layer;

implementing a second inductor in a second plurality of metal layers; and

coupling the second inductor to the center tap of the first inductor;

wherein the second inductor has a diameter that is less than a diameter of the first inductor.

16. The method of claim 15, wherein:

the integrated circuit comprises a plurality of metal layers extending from a lower metal layer to an upper metal layer; and

implementing a first inductor comprises forming the first inductor above the lower metal layer.

17. The method of claim 15, wherein:

implementing a first inductor comprises forming a fourth coil on a bottom layer of the first inductor and the second coil on a top layer of the first inductor; and

the first and second coils are formed having traces of smaller widths than traces of the third and fourth coils.

18. The method of claim 17, wherein implementing a first inductor comprises forming the third coil with a plurality of loops having traces of an outer loop with widths that are larger than widths of traces of an inner loop.

19. The method of claim 17, wherein implementing a first inductor comprises forming the fourth coil of the first inductor in a plurality of metal layers.

20. The method of claim 15, wherein implementing a second inductor in a second plurality of metal layers comprises implementing the second inductor outside of the first inductor.

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